SOLID STATE IMAGE SENSORS AND MICROLENS ARRAYS

Field of the Invention

The present invention relates to solid state image sensors of the type including an array of light sensitive elements (i.e., pixels) and, more

5   particularly, to solid state image sensors including an array of microlenses disposed in front of the pixel array.

Background of the Invention

10   A conventional solid state image sensor includes an array of light sensitive pixels. Not all of the area of each pixel is light sensitive. In a complementary metal-oxide semiconductor (CMOS) type image sensor, typically about 50% of the area of each

15   pixel is occupied by opaque, non-sensitive circuitry. Light impinging on the non-sensitive pixel area is not collected, resulting in a loss of sensitivity and degraded performance. This is illustrated schematically in FIG. 1, which shows two adjacent

20   pixels of a sensor array each including a sensitive area 200 surrounded by non-sensitive circuitry 202. Light 204 which strikes the sensitive areas 200

contributes to the sensor output signal. Light 206 which strikes the non-sensitive circuitry 202 is scattered and lost (i.e., not detected).

Such loss of sensitivity can be compensated for by the use of microlenses. As illustrated in FIG. 2, a microlens 208 is associated with each pixel. The microlens 208 covers both the sensitive and non-sensitive areas 200 and 202 of the pixel, collecting light from most of the total pixel area and focussing the collected light onto the sensitive area 200 of the pixel. Accordingly, a greater proportion of the light striking the pixel area is collected and, thus, the sensitivity of each pixel is improved. Typically, the use of microlenses approximately doubles the sensitivity of an equivalent sensor without microlenses. This technique is well known in the art as may be seen, for example, in U.S. Patent Nos. 4,861,140; 5,677,200; 5,250,798; and 5,614,590.

The arrangement shown in FIG. 2 is a simplification, showing only light rays which are perpendicular to the sensor surface so that the microlenses focus the light rays onto the center of the sensitive area 200 of each pixel. This is true at the optical axis of the image sensor but, for pixels located off-axis, the light rays are non-perpendicular to the sensor surface, as shown in FIG. 3.

Here, because the light rays are non-perpendicular, the area onto which the light rays are focussed is shifted away from the center of the sensitive area 200, but is still entirely within the sensitive area. The size of the shift is dependent

on the curvature and refractive index (i.e., the
focal length) of the microlens 208, the distance
between the microlens and the sensor surface, the
primary optics of the imaging system of which the
5   sensor forms a part, and the distance of the pixel
from the optical axis.

As long as the light collected by the
microlens 208 is focussed entirely within the
sensitive area 200 of the pixel, the shift of the
10   focussing spot is not significant. However, if the
shift is so extreme that the focussing spot is
shifted partly or wholly out of the sensitive pixel
area 200, as shown in FIG. 4, the pixel will fail to
detect some or all of the light, resulting in a loss
15   of sensitivity known as "vignetting." This is
particularly problematic with CMOS type image sensors
which include a greater number of metal layers than,
for example, CCD devices. As a result, there is a
larger distance between the microlens and the sensor
20   surface, and this increases the shift of the
focussing spot.

One attempt to address this problem is to
increase the exit pupil of the primary lens system,
but this is expensive and not cost effective for CMOS
25   sensors which are generally used in low-cost imaging
systems. Another attempt to address the problem of
vignetting is disclosed in U.S. Patent No. 5,610,390,
in which the position of the microlens relative to
the pixel is adjusted by an amount which varies with
30   the distance of the pixel from the optical axis of
the sensor array. This is illustrated in FIG. 5,
where the microlenses are shifted to the left by a
distance d, as compared with FIG. 4, so that the

focussing spots are shifted back into the sensitive areas 200 of the pixels. According to U.S. Patent No. 5,610,390, the optical axis of each microlens is displaced towards the central axis of the sensor

5   array by an amount which is proportional to the distance between the pixel and the central axis.

In theory, for a given sensor, microlens array and primary lens system, the spacing between adjacent microlenses may be adjusted, and hence their

10   positions varied relative to the pixel array, such that all of the light collected by each microlens is focussed on the center of the associated pixel. However, this solution would require different microlens arrays to suit the parameters of specific

15   imaging systems. Also, the relative microlens shifts required for adjacent pixels are so small that it is impractical to apply the necessary displacements to individual microlenses in the manner disclosed in U.S. Patent No. 5,610,390.

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Summary of the Invention

It is an object of the present invention to provide an improved image sensor having a microlens array which reduces vignetting while mitigating the

25   aforesaid disadvantages of the prior art.

This and other objects, features, and advantages are provided by a solid state image sensor which may include an array of pixels and a corresponding array of microlenses disposed in front

30   of the array of pixels. The positions of the microlenses relative to their corresponding pixels may vary according to the distances of the pixels from a central optical axis of the image sensor to

substantially eliminate vignetting of light collected by the microlenses. Further, the array of microlenses may be divided into blocks, each of the blocks may include a plurality of microlenses. Also,

5 within a particular block of microlenses, the positions of the microlenses relative to their corresponding pixels may be varied by an equal amount.

The microlenses within each of the blocks

10 may be substantially equally spaced apart by a first distance, and adjacent blocks of microlenses may be spaced apart by a second distance which is less than the first distance. Additionally, the microlenses may be substantially equally spaced throughout the

15 array of microlenses, and selected microlenses at the edges of the blocks may be smaller in at least one direction than the remainder of the microlenses of the blocks. More particularly, the blocks may be substantially rectangular. The blocks may also have

20 irregular edges configured such that the blocks are tessellated to form a substantially continuous array of microlenses.

A solid state image sensor according to the invention may include an array of pixels having a

25 first aspect ratio, and each of the pixels may include a light-sensitive area having a second aspect ratio. Moreover, the first aspect ratio may be substantially equal to the second aspect ratio.

Yet another aspect of the invention is for

30 an imaging system which may include a solid state image sensor as briefly described above. Additionally, a camera is also provided according to

the invention and may again include a solid state image sensor as briefly described above.

Brief Description of the Drawings

5   Embodiments of the invention will now be described, by way of example only, with reference to the accompanying drawings, in which:

FIG. 1 is a cross sectional view of a pixel array of a prior art solid state image sensor;

10   FIG. 2 is a cross sectional view of a microlens array applied to the pixel array of FIG. 1;

FIG. 3 is a cross sectional view illustrating off-axis illumination of the pixel array of FIG. 2;

15   FIG. 4 is a cross sectional view illustrating extreme off-axis illumination of the pixel array of FIG. 2, resulting in vignetting;

FIG. 5 is a cross sectional view illustrating the displacement of microlenses relative

20   to associated pixels to compensate for off-axis illumination according to the prior art;

FIG. 6 is a schematic block diagram of the geometry of an image sensor with a microlens array and a primary lens according to the present

25   invention;

FIGS. 7 and 8 are schematic block diagrams illustrating individual pixels and displacements of microlenses and focussed light spots relative thereto according to the present invention;

30   FIG. 9 is a schematic block diagram illustrating a first embodiment of part of a microlens array in accordance with the present invention;

FIG. 10 is a schematic block diagram illustrating a second embodiment of part of a microlens array in accordance with the present invention;

FIG. 11 is a schematic block diagram illustrating the difference between a rectangular block of microlenses and a castellated block of microlenses as used in embodiments of the present invention;

FIG. 12 is a schematic block diagram illustrating a third embodiment of part of a microlens array in accordance with the present invention including castellated blocks of microlenses;

FIG. 13 is a schematic block diagram illustrating a fourth embodiment of part of a microlens array in accordance with the present invention including castellated blocks of microlenses; and

FIG. 14 is a schematic block diagram illustrating the difference between a rectangular block of microlenses and a modified block of microlenses as used in various embodiments of the present invention.

Detailed Description of the Preferred Embodiments

Referring now to FIG. 6, an imaging system according to the present invention includes a solid state image sensor 10 having a length/width D, a microlens array 12 having a thickness t and a refractive index n, and primary lens system 14 having a focal length f_B. For a pixel at the edge of the sensor 10, the focussing spot is shifted away from

the center of the sensor as a result of off-axis
illumination by an amount s, where:

$$s = D \times t/(2 \times f_b \times n). \qquad (1)$$

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The corresponding microlens would have to be shifted
by the same amount in the opposite direction to
compensate for this. Equation (1) is simplified for
a one-dimensional (linear) sensor array, but is
10 easily extended to two dimensions for a rectangular
sensor array.

It will be understood that the present
analysis is applicable to a range of types of primary
lens systems including single- and multi-element
15 lenses. Turning now to FIG. 7, the corresponding
situation for a pixel 16 and microlens 18 located at
the top left hand corner of a two-dimensional sensor
array is illustrated. The microlens 18 is shifted
towards the center of the array in both the x and y
20 directions, the x and y components s_x and s_y each
being calculated using equation (1) and D_x and D_y as
the x and y dimensions of the array. The shift of
the microlens 18 relative to the pixel 16 results in
the focussed light spot 22 falling in the center of
25 the sensitive area 20.

Equation (1) depends on the focal length of
a specific primary lens system. This is
disadvantageous since the modified microlens array is
matched to a particular primary focal length,
30 restricting the range of different lenses that will
work with the sensor without vignetting. It is
desirable for a single sensor design to work with as
large a range of primary lenses as possible. In

order to maximize the range of possible primary
lenses, it is important to note that the focussed
light spot 22 does not need to fall in the center of
the sensitive area 20 to avoid vignetting. It is
5   only necessary that substantially all of the focussed
light falls somewhere within the sensitive area.

This concept is illustrated in FIG. 8,
where two focussed light spots 22a and 22b, as might
be produced using two different primary lenses having
10   different focal lengths, are shown. Both of the
light spots 22a and 22b are within the sensitive area
20 of the pixel 16. Accordingly, it can be seen that
a microlens position optimised for a given primary
focal length will also be acceptable for a range of
15   primary focal lengths. By way of example, one of the
primary lenses may be a telecentric lens (i.e., $f_B =$
∞), and the other may have a shorter focal length f_B
= f_{B2}. When the telecentric lens is used, light is
perpendicular to the image plane, so the focussed
20   light spot is directly beneath the center of the lens
(i.e., the shift s from equation (1) is equal to
zero).

If the microlens center 24 is positioned
above the center of the light spot 22a at the most
25   extreme acceptable position towards the central axis
of the sensor (i.e., the lower right of the pixel
sensitive area in this example where we are
considering the top left pixel of the sensor array),
then light from a telecentric lens will be focussed
30   at that position and the focussed light spot for any
shorter focal length will be shifted upwards and to
the left. The shortest acceptable focal length will
be that which produces the focussed light spot 22b at

position 26, and can be calculated according to the following equations:

$$s_{x1} = A_x/2 - d/2, \text{ and} \qquad (2.1)$$

$$s_{y1} = A_y/2 - d/2, \qquad (2.2)$$

where s_{x1} and s_{y1} are the required shifts in the x and y directions from the center of the sensitive area 20 to the position 24, A_x is the width of the sensitive area 20, A_y is the height of the sensitive area 20, and d is the diameter of the focussed light spot. By symmetry:

$$s_{x2} = A_x - d, \qquad (3.1)$$

and

$$s_{y2} = A_y - d, \qquad (3.2)$$

where s_{x2} and s_{y2} are the x and y shifts from position 24 to position 26. From equation (1), it follows that:

$$s_{x2} = D_x \times t/(2 \times f_{B2x} \times n), \qquad (4.1)$$

and

$$s_{y2} = D_y \times t/(2 \times f_{B2y} \times n), \qquad (4.2)$$

Furthermore, from equations (3) and (4) it follows that:

$$f_{B2x} = D_x \times t / (2 \times (A_x - d) \times n), \qquad (5.1)$$

and

$$f_{B2y} = D_y \times t / (2 \times (A_y - d) \times n). \qquad (5.2)$$

Thus, with respect to the x-axis, the sensor can be used with lenses with a range of back focal length between ∞ and f_{B2x} without any vignetting in the x-axis. The range in the y-axis will be determined by f_{B2y}. Since a lens has only one focal length, the range will be limited by whichever axis vignettes first. Preferably, $f_{B2x} = f_{B2y}$, thus:

$$D_x \times t / (2 \times (A_x - d) \times n) = D_y \times t / (2 \times (A_y - d) \times n),$$

which can be simplified to:

$$D_x / A_x = D_y / A_y, \qquad (6)$$

and rearranged to:

$$A_x / A_y = D_x / D_y \qquad (7)$$

From this analysis it follows that, for operation over a maximal range of lens focal lengths, the aspect ratio of the pixel's light sensitive area should be substantially equal to the aspect ratio of the image array as a whole. For example, if the image array has a 16:9 aspect ratio, the sensitive area of the pixel should also have a 16:9 aspect ratio to maximize the range of lenses that will

operate with the microlenses and not cause
vignetting.

As can be seen from equation (1), the
shifts required to provide optimal placement of each
5   microlens is proportional to the distance of each
pixel from the center of the image sensor (i.e., from
the optical axis of the primary lens system),
requiring a smooth, continuous shift of the center
positions of the microlenses as disclosed in U.S.
10   Patent No. 5,610,390. Typically, the difference in
shift between neighboring pixels would be on the
order of 10nm - 15nm. This is difficult if not
impossible to achieve in practice since the maximum
design resolution (i.e., the minimum snap-grid delta)
15   for semiconductor masks used in the manufacture of
image sensors and microlens arrays is on the order of
50nm - 100nm.

In accordance with the present invention,
the microlens array is divided into blocks, each
20   including a plurality of microlenses, and variations
in the parameters of the microlens array are applied
to blocks of microlenses rather than to individual
microlenses. This allows shifting of the microlenses
to be accomplished without any modification of
25   standard design or manufacturing technologies. The
invention can be applied at the design stage, with no
need to modify manufacturing processes, and is
therefore relatively easily implemented for high
volume production.

30   For practical purposes, the minimum
displacement which can be applied to a block of
microlenses is equal to the minimum snap-grid delta
determined by the process technology, as mentioned

above (typically 50 - 100nm). This dimension is
referred to hereinafter simply as Delta and is
smaller than the pixel size or feature size. The
frequency of the displacement (i.e., the block size)
5 may be selected such that the cumulative effect of
the displacements produce the required shift of the
microlenses. This approach may be implemented in two
basic ways, namely by varying the gap between
adjacent blocks of microlenses, as illustrated in
10 FIG. 9, and by varying the sizes of microlenses at
selected edges of blocks, as illustrated in FIG. 10.

Referring initially to FIG. 9, an array of
microlenses is illustrated which is divided into four
blocks. The lenses belonging to each of the four
15 blocks are identified as A, B, C, and D. The spacing
between each microlens within each block is g1, which
is greater than Delta. The spacing at the boundaries
between each adjacent block is g2, where g2 is less
than g1. If the optical axis of the array is at the
20 intersection of blocks A, B, C and D, it will be seen
that the effect of the reduced gaps g2 is to shift
the optical axis of each of the individual
microlenses within each block towards the optical
axis of the array. If this shift is repeated for
25 additional blocks surrounding the central blocks A,
B, C, and D, it will be seen that the cumulative
shift will increase for blocks at increasing
distances from the optical axis of the array.

The advantage of this implementation, in
30 which the gap g2 between adjacent blocks is narrowed
compared with the gap g1 between individual
microlenses within a block, is that the microlenses
are of constant size. This provides constant optical

performance and makes the block boundaries less visible. The disadvantage is that the minimum size of g2 is determined by the process technology, so g1 will likely be greater than the minimum possible gap

5 (the minimum possible gap size g1 = g2 + Delta), reducing the "fill factor" of the microlenses and thus degrading sensor performance by reducing sensitivity.

Referring now to FIG. 10, the alternative

10 is for the gaps between individual microlenses and blocks of microlenses to be kept constant (usually at the minimum possible value), and to reduce the sizes of those microlenses at the block boundaries so that the blocks as a whole are effectively shifted in a

15 manner similar to those of FIG. 9. As shown in FIG. 10, "normal" microlenses have a size m1 x m1, while the reduced size microlenses have a size m2 x m1 or m2 x m2. The minimum difference between m1 and m2 is again determined by the design/process Delta value m1

20 = m2 + Delta.

The advantage of this implementation is that the gap size between all microlenses may be maintained at a minimum, maximizing the fill factor and sensitivity. The disadvantage is the reduced

25 size of the microlenses at the block boundaries, which may reduce the sensitivity of the corresponding pixels and possibly give rise to visible patterning in the sensor output. Such patterning can be removed by calibrating the sensor using a white image and

30 scaling the pixel outputs appropriately, or by disguising the edges in a manner to be described below.

In each case, the value of Delta is determined by the design system and/or process technology in use. The total microlens shift required at the corners of the sensor can be calculated as described above. It then remains to determine the size of the block (number of pixels) which will provide the required shift at the corners, which can be calculated (for each axis x and y) as follows:

Block Size = INT (Delta x NPix / (2 x s)), (8)

where the block size is the number of rows/columns of pixels in a block, Delta is the change in size (of gap or microlens), Npix is the number of rows/columns of pixels in the array, and s is the microlens shift required at corners of the array. The INT (integer) function is used so that only a whole number of pixels will be shifted. For a typical image sensor array, the block size is likely to be in the range of about 4 to 10 rows/columns.

In both of the cases illustrated in FIGS. 9 and 10, the cumulative effect of the block shifts is to shift individual microlenses so that substantially all of the light collected by each microlens is focussed within the sensitive area of the associated pixel. However, both arrangements create discontinuities in the spatial sensitivity response of the sensor array due to changes in the effective fill factor of the microlenses at the boundaries of the blocks.

A high performance digital still camera would typically go through a calibration stage during

manufacture in which the black level offset and gain
of each pixel would be measured and stored in the
camera to compensate for non-uniformities caused by
manufacture of the image sensor. This technique

5   would also substantially eliminate the effect of the
sensitivity changes at the block boundaries of a
microlens array in accordance with the present
invention. However, this type of calibration adds
significantly to the cost of the camera as it

10   requires time and effort during manufacture and also
requires the camera to include memory devices to
store the correction parameters. Accordingly, this
technique is too expensive to use in low cost imaging
systems.

15   In accordance with a preferred feature of
the invention, visible patterning arising from the
discontinuities at the block boundaries may be
disguised by the following methods, without adding to
the cost of the sensor. As described above in

20   relation to FIGS. 9 and 10, the microlens array is
divided into regular rectangular blocks so that the
boundaries are straight lines. This causes visible
patterning in the sensor output which is particularly
apparent and undesirable. The boundaries may be

25   disguised and the resultant patterning made less
apparent by modifying the shapes of the blocks so
that their boundaries are irregular.

An example of this idea as applied to a 4x4
block of microlenses is illustrated in FIG. 11. It

30   should be noted that while a 4x4 block is
illustratively shown, the technique is applicable to
blocks of any size. A regular, rectangular block 30
is shown, alongside a modified block 32 in which

individual microlenses have effectively been displaced so that the edges of the block are "castellated." The total number of microlenses in the block remains the same, and a plurality of such modified blocks can be tessellated to form a continuous, uniform array. This technique can be applied both in the case where block shifts are effected by narrowing the gaps between blocks (FIG. 12) and in the case where block shifts are effected by reducing the size of microlenses at the block boundaries (FIG. 13).

In FIGS. 12 and 13, the individual microlenses making up four blocks are again identified as A, B, C and D. It will be understood that the size and shape of irregular blocks making up an array may vary from the illustrated examples, as long as the blocks are capable of being tessellated, i.e., as long as they can fit together to form a substantially uniform, continuous array. Suitable designs of block shapes can easily be achieved by starting with a rectangular block and moving a block from one side to the other. This is illustrated in FIG. 14, which shows a rectangular block 34 and a corresponding block with one microlens moved. The same movement can be applied to microlenses on more than one side of the starting block, as illustrated by the example of FIG. 11.

The present invention also relates to solid state image sensors incorporating microlens arrays of the types described above, and into imaging systems and cameras including such sensors. Furthermore, it will be appreciated that other improvements and

modifications may be incorporated without departing from the scope of the invention.